

RESEARCH ARTICLE

DEVELOPMENT AND CHARACTERIZATION OF CASSAVA STARCH-COATED BIODEGRADABLE PACKAGING SHEETS FROM CORN HUSK, CORN SILK, CASSAVA PEEL, AND BANANA PEEL WASTE

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Abstract

The accumulation of petroleum-derived single-use plastic packaging has created a strong need for biodegradable materials from renewable, low-cost resources. This study developed biodegradable packaging sheets coated with cassava starch using corn husk, corn silk, cassava peel, and banana peel waste. The raw materials were washed, cut, alkaline-pulped with sodium carbonate, blended into a homogeneous pulp, and formulated into three treatments by varying corn husk content (T1: 100 g, T2: 200 g, and T3: 300 g), while cassava peel, banana peel, and corn silk were kept constant. Bentonite, rosin-alum, and over-matured okra mucilage were incorporated to improve sheet formation and bonding. The molded sheets were sun-dried and coated on both surfaces with a cassava starch-polyvinyl alcohol bioplastic coating plasticised with glycerol. The developed sheets were evaluated for moisture content, water absorption, thickness, grammage, tensile strength, solubility, and soil-burial biodegradability. Significant treatment effects ($p < 0.05$) were observed for the major physical and mechanical properties. T3 showed the highest thickness (1.926 ± 0.029 mm), grammage (617.7 ± 16.41 g/m²), moisture content ($7.163 \pm 0.150\%$), water absorption ($385.5 \pm 11.42\%$), and tensile strength (2.1067 ± 0.03 MPa). However, biodegradation was fastest in T1, which reached $63.33 \pm 2.00\%$ weight loss after 49 days, compared with $52.00 \pm 2.00\%$ for T2 and $37.33 \pm 2.00\%$ for T3. All treatments showed low solubility ($<4\%$) in distilled water, acetic acid, sodium hydroxide, and ethanol after 24 h immersion. The results indicate that agricultural wastes can be converted into biodegradable single-use packaging sheets, with T3 offering better structural performance and T1 showing faster environmental degradation. Further hydrophobic coating optimization is recommended for wet food-contact applications.

Keywords: Agricultural waste; Biodegradable packaging; Cassava starch coating; Natural fiber composite

INTRODUCTION

Packaging materials are essential in modern food systems because they protect food, reduce contamination, support handling and distribution, and extend product availability throughout the supply chain (Ncube *et al.*, 2021). However, many food packaging formats are designed for single use and are commonly produced from petroleum-derived plastics. Although these plastics provide good mechanical strength, light weight, and moisture resistance, their persistence after disposal has raised concerns about plastic accumulation, microplastic formation, and inefficient

end-of-life management (Kossalbayev *et al.*, 2025). Therefore, replacing non-degradable single-use packaging with renewable, biodegradable materials compatible with local waste-management systems has become an important research priority.

Agricultural residues provide an attractive raw-material base for biodegradable packaging because they are abundant, low-cost, and rich in lignocellulosic fibers. Corn husk, corn silk, cassava peel, and banana peel are generated in large quantities during food preparation and agro-processing, yet they are commonly underutilized or discarded (Iewkittayakorn *et al.*,

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2020). These residues contain cellulose, hemicellulose, lignin, starch, and pectic substances that can contribute to sheet formation, bonding, and biodegradability. Previous studies have demonstrated the potential of agricultural residues and non-wood fibers for biodegradable plates, sheets, films, and composites (Iewkittayakorn *et al.*, 2020; Ishara *et al.*, 2024; Kossalbayev *et al.*, 2025).

Despite their environmental advantages, natural fiber-based packaging materials often suffer from high water absorption, brittleness, non-uniform thickness, and insufficient mechanical strength. These limitations are particularly important for food-contact packaging, where the material must maintain integrity during handling and short-term use (Ishara *et al.*, 2024). Reinforcement with natural binders, fillers, and bio-based coatings can improve sheet cohesion and surface resistance. Cassava starch is widely used in biodegradable film and coating systems due to its film-forming ability, biodegradability, and availability (Tharanathan, 2003). When combined with plasticizers such as glycerol and polymeric binders such as polyvinyl alcohol (PVA), starch-based coatings can improve flexibility and surface integrity while remaining largely biodegradable (Rhim *et al.*, 2013; Sanyang *et al.*, 2016).

Most previous studies have focused on single agricultural residues or starch-based films. Limited information exists on combining corn husk, corn silk, cassava peel, and banana peel into a single fiber-based packaging sheet reinforced with a cassava starch-PVA coating. This study therefore aimed to develop biodegradable packaging sheets from these agricultural wastes and evaluate how increasing corn husk content affected physical, mechanical, solubility, and biodegradation properties. The developed fiber-based material was primarily intended as a biodegradable cushioning and structural packaging material to reduce mechanical damage during transportation and to serve as a base material for molded containers such as egg trays and packaging for dry commodities. In addition to utilizing agricultural residues, the proposed production approach was designed to remain simple and low-cost,

making it potentially suitable for small-scale and household-level entrepreneurs. Sun-drying can reduce dependence on energy-intensive mechanical drying, lowering processing costs and energy consumption, although large-scale commercial production would require greater process control. Accordingly, the study focused on its physical, mechanical, solubility, and biodegradation characteristics. At the same time, the present scope did not consider advanced barrier properties such as water-vapour and gas permeability, as these are more critical for primary food-contact packaging requiring extended shelf-life protection.

MATERIALS & METHODS

Study location and experimental period

This study on biodegradable packaging material was conducted at the Food Science and Technology Laboratory, Department of Biosystems Technology, Faculty of Technology, South Eastern University of Sri Lanka, from November 2024 to April 2025.

Experimental design and treatment formulations

A Completely Randomized Design (CRD) was employed, with three treatments, each replicated three times ($n = 9$ experimental units), for a total of nine packaging sheet samples. The independent variable was the proportion of corn husk in the pulp mixture, while the quantities of cassava peel, banana peel, and corn silk were held constant across all treatments (Table 1). The study was conducted under controlled laboratory conditions, and we assumed environmental uniformity within the laboratory to minimize experimental error. We considered three independently prepared sheets as experimental replicates for each treatment. Where multiple test pieces or measurement points were obtained from an individual sheet for physical or mechanical analyses, these were treated as technical subsamples and were specified separately under the respective analytical methods.

Preparation of biodegradable packaging sheets

Corn husk and corn silk were obtained from local markets and farms in the Oluvil area.

Corn husk, which is rich in cellulose and hemicellulose, served as the main lignocellulosic reinforcing material and contributed to the structural strength and rigidity of the packaging sheets (Chawla *et al.*, 2023). Corn

silk contains both soluble and insoluble dietary fibers, including cellulose, hemicellulose, lignin and pectic components, and was incorporated as an additional fibrous component

Table 1: Composition of agricultural waste raw-material mixtures used in the T1-T3 biodegradable packaging sheet formulations

	Corn husk (g)	Cassava peel (g)	Banana peel (g)	Corn silk (g)
T1	100	200	100	10
T2	200	200	100	10
T3	300	200	100	10

Values represent the quantities of raw materials used in each treatment formulation. The corn husk content varied across treatments (T1: 100 g, T2: 200 g, and T3: 300 g), while the quantities of cassava peel, banana peel, and corn silk were kept constant across all treatments.

contributing to the fiber network (Singh *et al.*, 2022).

The cassava was purchased from the Agricultural Research Centre, Thelijjawila, and the peels were collected after processing. Cassava peel is a starch-rich fibrous residue containing starch and cellulose that can function as a matrix-forming and reinforcing material in biodegradable packaging (Afzia and Ghosh, 2026). Banana peels were collected from juice vendors in the Oluvil area and used promptly to avoid over-fermentation. Their starch, cellulose, and pectin fractions can contribute to film/sheet formation, inter-fiber binding, and biodegradability (Shiam *et al.*, 2024). Over-matured okra was obtained locally from the Oluvil area and used as a source of natural mucilage, which served as a bio-based binder because its polysaccharides can promote intermolecular interactions and improve cohesion within biopolymer matrices (Araújo *et al.*, 2018). All raw materials were collected fresh, washed thoroughly with clean water to remove surface contaminants, and processed within 24 hours of collection.

All agricultural waste materials (corn husk, corn silk, cassava peel, and banana peel) were washed thoroughly with clean water to remove dirt and surface contaminants, then cut into pieces approximately 3-5 cm to facilitate uniform processing (Figure 1a). The materials were then subjected to alkaline pulping. Each batch was boiled in a solution of 40 g sodium carbonate (Na_2CO_3) in 3 L distilled water at 100 °C for 60 minutes to soften the lignocellulosic fibers and promote pulp formation

(Steffen *et al.*, 2024). Sodium carbonate was selected as the pulping agent because of its lower toxicity, ease of handling, and established effectiveness for non-wood agricultural fiber pulping compared with sodium hydroxide-based systems (Steffen *et al.*, 2024). Following boiling, the softened material was drained through a sieve to remove excess liquor and then mechanically blended to a homogeneous slurry using a high-speed laboratory blender. The resulting base pulp was then divided by weight into three separate batches corresponding to the three treatment compositions (T1, T2, and T3) by adjusting the proportion of corn husk in accordance with the treatment formulations (Table 1), while keeping cassava peel, banana peel, and corn silk quantities constant (Figure 1b).

Each treatment pulp batch (T1, T2, and T3) was processed independently into packaging sheets using the same procedure to ensure comparability between treatments. Before casting the sheets, we incorporated two processing aids into each pulp batch. First, we added 5 g of bentonite clay as a reinforcing filler. Bentonite, an aluminosilicate clay mineral, improves fiber-matrix interaction by filling inter-fiber voids, thereby enhancing the structural integrity and barrier properties of the finished sheet (Shanmathy *et al.*, 2021). Second, 5 g of rosin–alum sizing agent was added to reduce the cellulose fiber network's hydrophilicity. Rosin sizing functions through the formation of aluminium rosin complexes on the fiber surface: alum (aluminium sulfate) lowers pulp pH to the optimal range of 4.5-5.5, and precipitates rosin onto the fibers

as a hydrophobic coating, reducing liquid penetration and improving the moisture resistance of the sheet (Gess, 1996). The pH of the pulp was verified to fall within this range before mold casting to ensure effective sizing.

Additionally, 100 mL of mucilage extract prepared from over-matured okra (*Abelmoschus esculentus*) was added to each batch as a natural, bio-based binder. Okra mucilage is rich in water-soluble polysaccharides containing hydroxyl (–OH) and carboxyl (–COOH) functional groups, which promote inter-fiber hydrogen bonding and improve cohesion within the fiber network (Murtaza *et al.*, 2022). The mucilage was prepared by boiling 200 g of chopped over-matured okra in 200 mL of distilled water for 20 minutes, followed by straining through a fine-mesh sieve and collecting the resulting viscous liquid for immediate use.

Each treatment pulp was mixed thoroughly to achieve a uniform consistency before being poured into standardized rectangular molds measuring 30 × 21 cm. The filled molds were levelled to ensure even sheet thickness and then sun-dried for approximately 48 hours under ambient conditions. After drying, the sheets were carefully removed from the molds and stored in sealed containers under desiccated conditions until the bioplastic coating step.

A bioplastic coating solution was prepared from cassava starch to improve the moisture resistance and mechanical durability of the packaging sheets. The bioplastic coating solution was formulated based on the method described by Omoike *et al.* (2024), with modifications adapted to the coating application context of this study. The formulation consisted of 10 g of extracted cassava starch dispersed in 50 mL of distilled water. Acetic acid (2 mL) was added as a formulation modifier to promote starch disruption and dispersion during heating and to help maintain the disrupted starch structure after heating. This action facilitates starch solubilization and supports the formation of a more homogeneous film-forming solution, consistent with its use in starch-based bioplastic formulations (Ishara

et al., 2024; Singh *et al.*, 2025). Glycerol (2 mL) was added as a plasticizer to improve the flexibility of the resulting coating film by intercalating between starch polymer chains and substituting strong intramolecular hydrogen bonds, thereby reducing brittleness and enhancing elongation at break (Tarique *et al.*, 2021). Polyvinyl alcohol (PVA: 1 g) was incorporated as a polymeric binder to strengthen the starch matrix; PVA improves the mechanical properties and film-forming capacity of starch-based coatings through hydrogen bond formation between the hydroxyl groups of PVA and starch, and partially counteracts the moisture sensitivity inherent to starch films (Omoike *et al.*, 2024; Deng *et al.*, 2024).

The complete mixture was placed in a double-boiler system and heated with continuous stirring for 15 minutes until a transparent, uniform, viscous solution formed, indicating complete starch gelatinization and polymer blending. The coating solution was allowed to cool to approximately 40 °C before application to prevent thermal damage to the dried fiber sheets (Figure 1c).

Each dried fiber sheet was placed on a clean, flat surface and coated uniformly on both sides using a wide flat brush, applying one coat per side (Figure 1c). Care was taken to achieve an even coating layer with no pooling at edges. The coated sheets were placed in a hot-air oven and dried at 50 °C for 1 hour to allow the coating to cure and adhere to the fiber substrate. The low drying temperature was selected to avoid thermal degradation of the starch coating and to ensure gradual, even moisture loss (Omoike *et al.*, 2024). The bioplastic coating enhanced the water resistance, surface strength, and flexibility of the final packaging material by forming a continuous polymer layer over the lignocellulosic fiber substrate, completing the sequence of raw-material preparation, pulping, sheet formation, drying, and coating (Figure 1).

Determination of physicochemical and mechanical characteristics

Moisture content

Moisture content was determined following the method of Akmeemana *et al.* (2024), with

minor modifications. Each dried fiber sheet ($n=3$) was cut into approximately 5 g samples. The initial weight (W_0) was recorded. Samples were oven-dried at 105 °C until con-

stant weight was achieved (W_1), then cooled in a desiccator before re-weighing. Moisture content (%) was calculated as:



Figure 1: Sequential preparation of biodegradable fiber-based packaging sheets: (a) raw material preparation and pretreatment; (b) pulping, blending, and sheet formation; and (c) drying and application of cassava starch–PVA coating. T1:100 g, T2:200 g, and T3: 300 g corn husk content

$$\text{Moisture content (\%)} = [(W_0 - W_1) / W_0] \times 100$$

Where; W_0 : Initial (pre-drying) sample weight, W_1 : Oven-dried sample weight

Eq. 1

Water absorption

Water absorption capacity of the fiber sheets ($n=3$ per treatment) was measured following the method described by Ishara *et al.* (2024). Each sheet was cut into 1×2 cm² pieces and weighed (initial weight; W_0). Samples were fully immersed in 100 mL distilled water at

room temperature for 24 hours. After immersion, excess surface moisture was blotted off, and the final weight (W_1) was recorded immediately. Water absorption (%) was calculated as:

$$\text{Water absorption (\%)} = [(W_1 - W_0) / W_0] \times 100$$

Eq. 2

Sheet thickness

Sheet thickness was determined following Gunathilake and Somendrika (2024), with minor modifications. A micrometer screw gauge (Mitutoyo Corp., Japan; resolution: 0.001 mm) was used to measure thickness at five randomly selected points across each sheet. The mean value was reported.

Grammage

Grammage was determined following Iewkit-tayakorn *et al.* (2020), with minor modifications. Test pieces of 500 - 1000 cm² were cut from each sheet ($n=20$ per treatment), weighed on a calibrated analytical balance, and grammage (g/m²) calculated as:

$$\text{Grammage (g/m}^2\text{)} = (m / A) \times 10,000$$

Where; m: Mass of the test piece (g), A: Area (cm²)

Eq. 3

Tensile strength

Tensile strength was tested following Iewkitayakorn *et al.* (2020) on an Instron Universal Testing Machine (Model ETM-5; Instron Corp., USA; load cell: 1 kN). Test strips of 25 ± 1 mm width and 180 ± 2 mm length were cut from each sheet ($n=12$ per treatment). The crosshead speed was $5 \text{ mm/min} \pm 2.5 \text{ mm/min}$. Parameters recorded included elongation at break, force to break, strain at break, and tensile stress at break (MPa). For comparison of the effect of coating on tensile strength, specimens were obtained from fiber sheets before application of the cassava starch-PVA coating (uncoated samples) and from the corresponding sheets after coating and curing (coated samples). Both coated and uncoated

specimens were cut to the same dimensions and tested under identical tensile-testing conditions.

Solubility assessment in different solvents

Solubility tests were conducted following Joseph *et al.* (2024), with modifications. Fiber sheet samples from each treatment ($n=3$ per treatment per solvent; total $n=9$ per solvent) were cut into 2×2 cm pieces, weighed, and fully immersed in 50 mL of the following solvents for 24 hours at room temperature: distilled water, acetic acid (5% v/v), sodium hydroxide (0.1 M), and ethanol (95% v/v). Post-immersion, physical changes (color, shape, surface integrity, and weight change) were recorded. Solubility (%) was calculated as:

$$\text{Solubility (\%)} = [(W_0 - W_1) / W_0] \times 100$$

Where; W₀: Initial dry weight, W₁: Dry weight after solvent immersion

Eq. 4

Determination of biodegradability

Biodegradability was assessed following Akmeemana *et al.* (2024), with modifications. Fiber sheet samples were cut into 2×2 cm pieces and weighed (W₀). Samples from each treatment ($n=3$) were buried in agricultural loam soil (organic matter ~3.5%; moisture content ~25%) at a depth of 3 cm in individual mesh-lined wire cages to facilitate sample recovery and prevent contamination with soil particles. All treatments were exposed to the

same soil type, burial depth, and moisture conditions to minimize environmental variability, although soil microbial activity was not independently quantified. Samples were retrieved every seven days over a 49-day (7-week) period. Upon retrieval, samples were gently brushed to remove soil, dried at 60 °C for 2 hours to remove moisture, and reweighed (W₁). Weight loss (%) was calculated as:

$$\text{Weight loss (\%)} = [(W_0 - W_1) / W_0] \times 100$$

Eq. 5

Visual observations (surface softening, fragmentation, discoloration) were recorded photographically at each retrieval interval and are presented as a supplementary qualitative record.

Statistical analysis

Statistical analyses were performed using Minitab Statistical Software (Version 22.0; Minitab LLC, USA). One-way analysis of variance (ANOVA) was conducted to assess differences among treatments for each physical and mechanical parameter. Where significant differences were detected ($p < 0.05$),

means were separated using Duncan's Multiple Range Test (DMRT).

RESULTS AND DISCUSSION

All three formulations produced intact and self-supporting fiber-based packaging sheets, with visible differences in surface texture, compactness, and thickness associated with variations in corn husk content (Figure 2).

Moisture content of biodegradable packaging sheets

The mean moisture content of the developed biodegradable packaging sheets ranged from

$4.80 \pm 0.42\%$ (T1) to $7.16 \pm 0.15\%$ (T3), with T2 at an intermediate $5.29 \pm 0.19\%$ (Table 2). One-way ANOVA revealed a significant effect of treatment on moisture content ($p <$

0.05). DMRT indicated that T3 was significantly higher than both T1 and T2, while T1 and T2 did not differ significantly from each other.

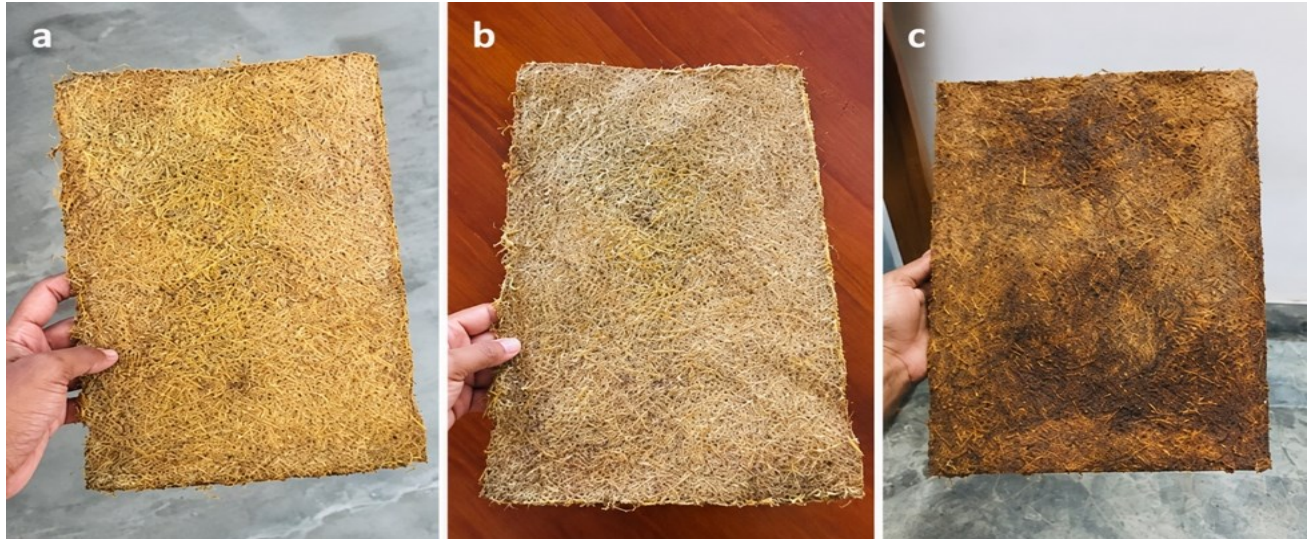


Figure 2: Visual appearance of the developed biodegradable fiber-based packaging sheets produced using the (a) T1:100 g, (b) T2:200 g, and (c) T3:300 g corn husk content

The moisture content values recorded in this study (4.80 - 7.16%) were lower than those reported for films prepared from agricultural residues such as grapevine cellulose (10.37 - 11.78% ; Paudel *et al.*, 2025) and cassava pomace films (~ 9 - 12% ; Akmeemana *et al.*, 2024). The relatively low moisture content

observed may be attributed to the combined effect of sodium carbonate pre-treatment, which removes some hygroscopic hemicellulose fractions, and the bioplastic coating, which reduces surface-level moisture exchange (Ishara *et al.*, 2024).

Table 2: Moisture content of biodegradable packaging sheets produced under the T1-T3 formulations

Type of packaging sheet	Mean moisture content (%)
T3	7.16 ± 0.15^a
T2	5.29 ± 0.19^b
T1	4.80 ± 0.42^b

The values are means of replicates of moisture content $\pm$ standard deviation; within a column, means followed by the same letters are not significantly different by Duncan's Multiple Range Test at $p < 0.05$, and different letters above the means were significantly different across the columns. Where: T1:100 g, T2:200 g T3:300 g corn husk content

From a packaging standpoint, moisture contents below 10% are generally considered acceptable for fiber-based biodegradable materials, as higher values compromise mechanical integrity and promote microbial proliferation (Kossalbayev *et al.*, 2025). The progressive increase in moisture content from T1 to T3 is consistent with the higher fiber density in T3, which contains more hygroscopic cellulose and hemicellulose from the additional corn husk, both known to carry abundant free

hydroxyl groups that interact with ambient moisture (Mohd Zaini *et al.*, 2023; Ayaşan *et al.*, 2020).

Water absorption of biodegradable packaging sheets

The developed biodegradable fiber sheets showed significant differences in water absorption among the treatments ($p < 0.05$). T3 recorded the highest mean water absorption ($385.5 \pm 11.42\%$), followed by T2 ($308.3 \pm$

15.55%), while T1 showed the lowest value ($257.1 \pm 8.62\%$) (Table 3). The comparatively high water absorption across all treatments indicates the hydrophilic nature of the devel-

oped sheets, attributable to natural lignocellulosic fibers with hydroxyl-rich components that absorb and retain water.

Table 3: Water absorption of biodegradable packaging sheets produced under the T1-T3 formulations

Type of packaging sheet	Mean water absorption (%)
T 3	385.5 ± 11.42^a
T 2	308.3 ± 15.55^b
T 1	257.1 ± 8.62^b

The values are means of replicates of water absorption $\pm$ standard deviation; within a column, means followed by the same letters are not significantly different by the Duncan’s Multiple Range Test at $p < 0.05$ and different letters above the means were significantly different across the columns. Where: T1:100 g, T2:200 g, T3:300 g corn husk content.

The high-water absorption values (257-386%) recorded across all treatments are characteristic of natural fiber-based packaging materials, reflecting the intrinsically hydrophilic nature of their major structural biopolymers, cellulose, hemicellulose, and pectin, which are rich in hydroxyl and carboxyl groups that form hydrogen bonds with water molecules (Kossalbayev *et al.*, 2025). The significantly higher water absorption of T3 than T1 and T2 is consistent with its higher corn husk content; corn husk contains a high proportion of hemicellulose (Mohd Zaini *et al.*, 2023; Ayaşan *et al.*, 2020), which is particularly susceptible to moisture uptake due to its branched, amorphous structure. The parallel increase in moisture content and water absorption from T1 to T3 indicates a positive association between these properties, likely because a greater proportion of hydrophilic lignocellulosic components promotes water binding through their hydroxyl and carboxyl groups (Ishara *et al.*, 2024; Kossalbayev *et al.*, 2025). These values are higher than those reported for pineapple leaf pulp plates (Iewkittayakorn *et al.*, 2020), suggesting that the moisture barrier properties of the current material require further improvement before practical application in humid or wet food-contact environments. For use as packaging plates or trays for dry or semi-dry food products, the water absorption levels of T1 and T2 may be acceptable, but T3 would require an additional hydrophobic barrier coating to perform reliably.

Thickness of biodegradable packaging sheets

The developed biodegradable fiber sheets showed significant differences in thickness among the treatments ($p < 0.05$). The mean thickness ranged from 1.215 ± 0.024 mm to 1.926 ± 0.029 mm, with the highest value recorded for T3, followed by T2 (1.368 ± 0.031 mm), while T1 showed the lowest thickness (1.215 ± 0.024 mm) (Figure 3). The thickness of the biodegradable packaging sheets increased progressively with corn husk content, ranging from 1.215 mm (T1) to 1.926 mm (T3), and all three treatments differed significantly ($p < 0.05$). This trend reflects the direct contribution of increased fiber mass to sheet volume during molding and drying.

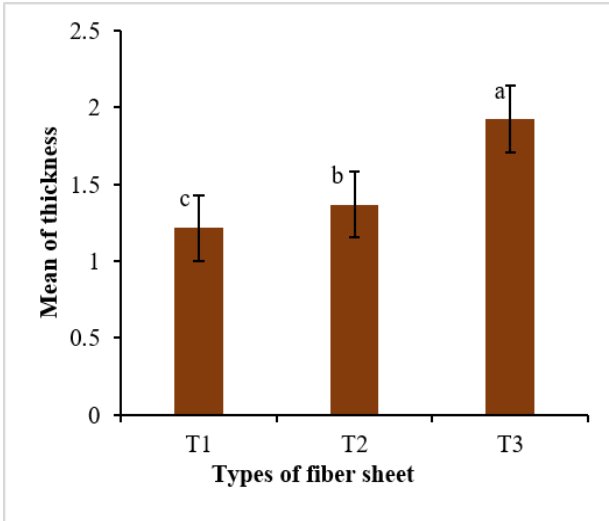


Figure 3: Effect of treatment formulation on the mean thickness of biodegradable packaging sheets. Where: T1:100 g, T2: 200 g, T3:300 g corn husk content

The recorded thickness values align with those reported for biodegradable packaging composites made from rice husk and wheat straw (1.5-2.1 mm; Ncube *et al.*, 2021) and pineapple leaf pulp sheets (Iewkittayakorn *et al.*, 2020), confirming that the current materials fall within an established and practically relevant range. The uniform thickness profile across replicates within each treatment demonstrates the reproducibility of the controlled blending, molding, and sun-drying protocol used. The bioplastic coating applied after sheet formation likely contributed to this consistency by filling surface micro-voids and producing a more compact, even surface layer. From a packaging perspective, thicker sheets generally offer improved mechanical strength and barrier properties, though they may reduce flexibility; T3's thickness, in particular, suggests suitability for semi-rigid packaging applications such as trays or plates.

Grammage of biodegradable packaging sheets

The grammage of the developed biodegradable packaging sheets varied among the treatments. T3 recorded the highest mean grammage ($617.7 \pm 16.41 \text{ g/m}^2$), followed by T2 ($539.6 \pm 16.52 \text{ g/m}^2$), while T1 showed the lowest value ($414.5 \pm 39.69 \text{ g/m}^2$) (Figure 4). No significant difference was observed between T2 and T3 ($p > 0.05$), whereas T1 had a significantly lower grammage than both T2 and T3 ($p < 0.05$). This pattern indicates that increasing fiber loading beyond the T2 level yields diminishing incremental returns in mass per unit area, possibly because sun-drying approaches compaction limits, beyond which additional fiber redistributes into thickness rather than contributing to areal density.

The finding is consistent with Iewkittayakorn *et al.* (2020), who reported that grammage in handmade pulp-based sheets is directly governed by the amount of pulp used per mold area, and that this relationship plateaus at higher fiber loads due to physical packing constraints. Higher grammage in T2 and T3 indicates denser, more structurally robust sheets, which correlates with the superior tensile strength observed in these treatments. For food packaging applications, higher gram-

mage generally improves load-bearing capacity and tear resistance; the values obtained here are suitable for lightweight dry food packaging, though further optimization would be needed for heavier or moisture-exposed applications.

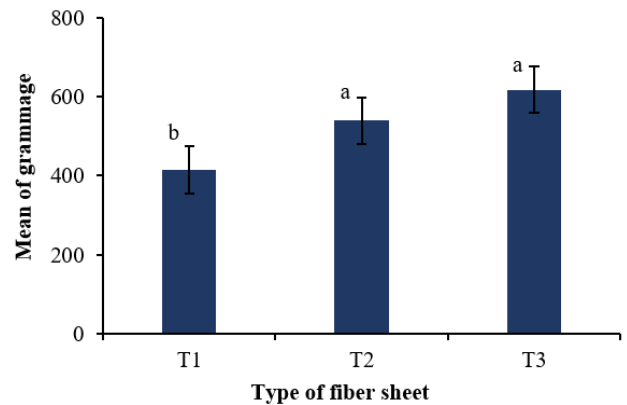


Figure 4: Effect of treatment formulation on the mean grammage of biodegradable packaging sheets. Where: T1:100 g, T2:200 g, T3:300 g corn husk content

Tensile strength of biodegradable packaging sheets

The tensile strength of the developed biodegradable fiber sheets varied among the treatments. T3 showed the highest mean tensile strength ($2.1067 \pm 0.03 \text{ MPa}$), followed by T2 ($1.849 \pm 0.15 \text{ MPa}$), while T1 recorded the lowest value ($1.4473 \pm 0.08 \text{ MPa}$) (Figure 5). T3 exhibited a significantly higher tensile strength than T1 ($p < 0.05$), whereas T2 showed an intermediate value that was not significantly different from either T1 or T3. The comparatively higher tensile strength of T3 may be associated with its greater thickness and grammage, together with improved fiber-matrix interactions that enhanced the load-bearing capacity of the sheet.

The tensile strength values recorded (1.447-2.107 MPa) are in the lower range for natural fiber composites, but comparable to values reported for handmade paper and fiber-based biodegradable packaging produced from similar agricultural residues (Iewkittayakorn *et al.*, 2020; Suriani *et al.*, 2021). The progressive improvement in tensile strength from T1 to T3 is attributable to the denser fiber network formed with increasing corn husk content,

which promotes greater fiber-to-fiber bonding and load transfer efficiency. This is consistent with the established principle that tensile performance in natural fiber composites scales positively with fiber content up to an optimal

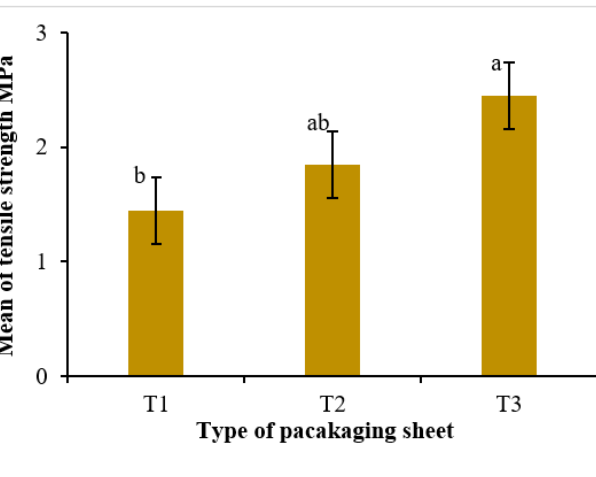


Figure 5: Effect of treatment formulation on the mean tensile strength of biodegradable packaging sheets. Where: T1:100 g, T2:200 g T3:300 g corn husk content

loading level (Mohan and Kanny, 2018; Syduzzaman *et al.*, 2020). The absence of a statistically significant difference in tensile strength between coated and uncoated sheets indicates that the cassava starch-PVA bioplastic coating primarily improves surface-level properties (smoothness, water resistance) rather than conferring bulk structural reinforcement, in agreement with findings by Azeredo *et al.* (2018) and Abdul Khalil *et al.* (2018). For single-use dry food packaging plates, T3 tensile strength is adequate; however, for heavier or moist food items, composite reinforcement strategies (e.g., incorporating natural fibres such as jute or hemp) should be explored.

Effect of cassava starch-PVA coating on tensile strength

The coated T3 biodegradable fiber sheets showed a slightly higher mean tensile strength (1.735 ± 0.20 MPa) than the uncoated T3 sheets (1.437 ± 0.11 MPa) (Figure 6). However, the difference between coated and uncoated sheets was not statistically significant ($p > 0.05$). The slight improvement after coating may be attributed to the formation of a continuous polymer layer on the sheet surface,

which enhanced surface cohesion and helped distribute applied stress across the fiber network. However, it did not substantially increase the material's overall structural strength. Other studies have found similar trends in which biopolymer coatings enhanced surface properties and moisture resistance without significantly impacting the mechanical strength of biodegradable films (Azeredo *et al.*, 2018; Abdul Khalil *et al.*, 2018).

Soil-burial biodegradability based on weight loss

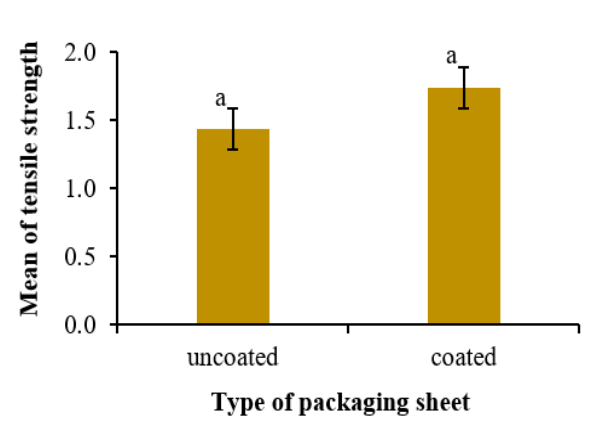


Figure 6: Comparison of mean tensile strength between uncoated and cassava starch-PVA-coated biodegradable T3 fiber sheets. Where: T3:300 g corn husk content

The gravimetric biodegradability data demonstrated a clear treatment-dependent degradation profile over the 49-day burial period (Table 4).

The percentage weight loss increased progressively across all treatments throughout the 49-day soil burial period, indicating gradual biodegradation of the packaging material. No weight loss was observed at day 0 in any treatment. After 7 days of burial, T1 showed the highest weight loss ($8.00 \pm 0.67\%$), followed by T2 ($5.33 \pm 0.67\%$) and T3 ($2.67 \pm 0.67\%$). This trend continued throughout the experimental period, with T1 consistently recording significantly higher weight loss than T2 and T3.

At the end of the 49-day burial period, T1 showed the greatest biodegradation, with a weight loss of $63.33 \pm 2.00\%$, followed by T2

at $52.00 \pm 2.00\%$. T3 showed the lowest weight loss, reaching only $37.33 \pm 2.00\%$ after 49 days. Significant differences among treatments at each burial period indicate that

the treatments differed in biodegradation behaviour.

Overall, the results demonstrate that biodegra-

Table 4: Weight loss of biodegradable packaging sheets during 49 days of soil-burial biodegradation

Burial period (days)	T1 Weight loss (%)	T2 Weight loss (%)	T3 Weight loss (%)
0	0.00 ± 0.00^a	0.00 ± 0.00^a	0.00 ± 0.00^a
7	8.00 ± 0.67^a	5.33 ± 0.67^b	2.67 ± 0.67^c
14	16.00 ± 1.33^a	12.00 ± 1.33^b	7.33 ± 0.67^c
21	26.00 ± 1.33^a	19.33 ± 1.33^b	12.67 ± 1.33^c
28	36.00 ± 2.00^a	28.00 ± 1.33^b	18.67 ± 1.33^c
35	46.67 ± 2.00^a	36.67 ± 2.00^b	25.33 ± 1.33^c
42	55.33 ± 2.00^a	44.00 ± 2.00^b	31.33 ± 2.00^c
49	63.33 ± 2.00^a	52.00 ± 2.00^b	37.33 ± 2.00^c

The values are means of replicates of weight loss % $\pm$ standard deviation; within a column, means followed by the same letters are not significantly different by Duncan's Multiple Range Test at $p < 0.05$, and different letters above the means were significantly different across the columns. Where: T1:100 g, T2:200 g, T3:300 g corn husk content

dability increased with burial duration, and the degradation rate followed the order $T1 > T2 > T3$. Values with different superscript letters within the same row indicate significant differences among treatments at $p < 0.05$. T1's faster degradation rate than T2 and T3 is consistent with its lower corn husk content and, correspondingly, a higher proportion of banana peel and cassava peel, both of which contain more readily biodegradable starch, pectin, and amorphous hemicellulose fractions susceptible to rapid enzymatic hydrolysis by soil microorganisms. In contrast, T3 degraded more slowly because its elevated cellulose and lignin content from corn husk includes lignin, a well-established recalcitrant biopolymer that resists microbial depolymerization (Kossalbayev *et al.*, 2025). Complete or near-complete biodegradation within the 7-week study period for T1 and T2 compares favourably with natural-fiber biodegradable packaging materials reported in the literature (Akmeemana *et al.*, 2024; Gunathilake and Somendrika, 2024). These findings confirm that the developed materials meet the fundamental requirement of biodegradability for sustainable packaging applications.

A limitation of the present biodegradation study was the absence of an uncoated control; therefore, the specific influence of the cassava starch-PVA coating on the degradation

rate could not be independently determined. Future studies should compare coated and uncoated sheets under identical soil-burial conditions.

Visual progression of soil-burial degradation

Environmental conditions such as moisture, temperature, nutrient availability, and microbial activity, as well as the material's size, surface area, and inherent degradability, influence biodegradation. The biodegradability of the developed packaging sheets was evaluated under natural soil conditions for seven weeks. Three samples from each treatment were buried, and degradation was monitored visually at 7-day intervals because the sheets progressively fragmented, preventing reliable mass-loss measurements (Figure 7).

During the first week, Treatment 1 (T1) showed visible signs of degradation, including surface softening and edge breakdown. Treatment 2 (T2) showed minor signs of wear, while Treatment 3 (T3) remained mostly intact with little visible change. This early-stage difference indicates that T1, with the lowest corn husk content, is more susceptible to microbial attack and environmental breakdown. The relatively high banana and cassava peel content in T1 might contribute to quicker decomposition.

By the end of the 7th week, most T1 samples had decomposed significantly, followed by T2. T3 showed the slowest degradation rate, with small amounts of material still visible. This slower degradation rate in T3 can be at-

tributed to its higher corn husk content, which includes more cellulose and lignin components known for their resistance to rapid biodegradation. The results demonstrate that the composition of agricultural waste significant-



Figure 7: Visual progression of soil-burial degradation of T1–T3 biodegradable packaging sheets over 49 days: (a) 0 days, (b) 7 days, (c) 14 days, (d) 21 days, (e) 28 days, (f) 35 days, (g) 42 days, and (h) 49 days

ly affects the biodegradation rate of packaging material. Lower corn husk content favors quicker biodegradation, while higher fiber content enhances strength but slows down decomposition.

Solubility of biodegradable packaging sheets in different solvents

The developed biodegradable packaging sheets showed low solubility in all tested solvents, with values remaining below 4% after 24 h of immersion (Table 5).

In distilled water, T1 showed the highest solubility ($2.13 \pm 0.15\%$), followed by T2 ($1.72 \pm 0.12\%$) and T3 ($1.28 \pm 0.10\%$). A similar decreasing trend from T1 to T3 was observed in acetic acid and ethanol. Overall, ethanol showed the lowest solubility, indicating that the fibre-based packaging sheets

were relatively resistant to dissolution in the tested organic solvent. In contrast, solubility in 0.1 M NaOH was slightly higher than in the other solvents, particularly for T3 ($3.68 \pm 0.25\%$), followed by T2 ($3.24 \pm 0.22\%$) and T1 ($2.87 \pm 0.20\%$). This may be due to partial alkali-induced swelling or surface modification of fiber components. A slight surface discoloration was observed in T2 and T3 after immersion in NaOH; however, no complete structural disintegration was observed. Overall, the low solubility values indicate that the developed biodegradable packaging sheets had good solvent resistance under the tested conditions.

Similar observations were reported by Rhim *et al.* (2013), who found that plasticized starch-based biopolymers show limited solubility in polar solvents. Tharanathan (2003) also emphasized the resistance of polysaccha-

ride-based films to mild acids and alcohols, while Sanyang *et al.* (2016) demonstrated that alkaline conditions may cause only superficial

changes in biopolymer films. These findings support the material's robustness and suitability

Table 5. Solubility of biodegradable packaging sheets in distilled water, acetic acid, sodium hydroxide, and ethanol after 24 h immersion

Solvent	T1 Solubility (%)	T2 Solubility (%)	T3 Solubility (%)
Distilled water	2.13 ± 0.15 ^a	1.72 ± 0.12 ^b	1.28 ± 0.10 ^c
Acetic acid (5% v/v)	2.46 ± 0.18 ^a	2.05 ± 0.16 ^b	1.63 ± 0.14 ^c
NaOH (0.1 M)	2.87 ± 0.20 ^c	3.24 ± 0.22 ^b	3.68 ± 0.25 ^a
Ethanol (95% v/v)	0.92 ± 0.08 ^a	0.76 ± 0.06 ^b	0.58 ± 0.05 ^c

The values are means of replicates of solubility % ± standard deviation; within a column, means followed by the same letters are not significantly different by Duncan's Multiple Range Test at $p < 0.05$, and different letters above the means were significantly different across the columns. Where: T1:100 g, T2:200 g, T3:300 g corn husk content

ity for environmentally friendly packaging applications.

The low solubility of the packaging sheets across all treatments in water, acetic acid (5% v/v), NaOH (0.1 M), and ethanol (95% v/v) reflects the chemical stability conferred by the composite material structure. The cross-linked network formed by cassava starch gelatinization in the presence of PVA and glycerol, combined with the entanglement of natural cellulose fibers, creates a matrix resistant to polar and mildly acidic or alkaline solvents (Rhim *et al.*, 2013; Tharanathan, 2003). The slight surface discolouration observed in NaOH without structural degradation is consistent with superficial saponification of ester linkages in the starch-PVA matrix, as previously documented for biopolymer films under alkaline conditions (Sanyang *et al.*, 2016). The high solvent resistance of all three treatments supports their suitability for food packaging contexts where incidental exposure to moisture, mild acids (e.g., food acidulants), or mild alkalis (e.g., cleaning agents) may occur.

CONCLUSION

The research shows that agricultural waste-corn silk, corn husk, cassava peel, and banana peel can be used to create biodegradable packaging materials by transforming them into fiber-based sheets and plates with natural additives and bioplastic coating. Physical and mechanical testing showed that the materials had suitable grammage, tensile strength, and moisture resistance, and that adding a bio-

plastic coating of cassava starch, PVA, acetic acid, and glycerol further improved water resistance and durability, as shown by substantial biodegradation within seven weeks in soil. The developed sheets are therefore better considered biodegradable cushioning materials or base substrates for moulded packaging such as egg trays and dry-commodity containers, rather than primary high-barrier food packaging materials. Future studies may investigate moisture- and gas-barrier properties if the material is intended for direct food-contact applications. The materials still do not reach the permeability and long-term stability of synthetic plastics, but they provide a biodegradable, low-cost alternative that benefits the environment and economy, making them worthy of further development, industrial scaling, and policy integration toward a circular economy.

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AUTHOR CONTRIBUTION

HAPWH conceived the research idea and designed the study. KOK conducted the experimental work and collected the data. KOK performed data analysis under the guidance of HAPWH and KOK and RMIKR prepared the

original draft under the supervision of HAPWH. HAPWH provided technical guidance and critically revised the manuscript. All authors read and approved the final manuscript.

Declaration of conflict of interest

The authors declare no conflict of interest.

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